Orbital angular momentum mode-demultiplexing scheme with partial angular receiving aperture

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Abstract: For long distance orbital angular momentum (OAM) based transmission, the conventional whole beam receiving scheme encounters the difficulty of large aperture due to the divergence of OAM beams. We propose a novel partial receiving scheme, using a restricted angular aperture to receive and demultiplex multi-OAM-mode beams. The scheme is theoretically analyzed to show that a regularly spaced OAM mode set remain orthogonal and therefore can be de-multiplexed. Experiments have been carried out to verify the feasibility. This partial receiving scheme can serve as an effective method with both space and cost savings for the OAM communications. It is applicable to both free space OAM optical communications and radio frequency (RF) OAM communications.

OCIS codes: (050.4865) Optical vortices; (060.2605) Free-space optical communication; (060.4230) Multiplexing; (070.6120) Spatial light modulators.

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1. Introduction

Angular momentum is one of the fundamental physical properties of electromagnetic waves and is generally decomposed into spin angular momentum (SAM) and orbital angular momentum (OAM) [1]. Compared with SAM, OAM is of much more interest for data transmission. As SAM associated with the polarization states of electromagnetic waves only offers limited channels; while OAM can have unlimited eigenstates (names OAM modes) that are orthogonal among one another, thus is allowed in principle to offer many channels so as to increase the transmission capacity. In the last few years OAM-based communications have drawn much attention both in optical and radio frequency (RF) regime [2–5]. Different OAM beams are multiplexed in free space optical communications to achieve high spectral efficiency and capacity of multi-Tbit/s [2]. It is also verified that OAM multiplexing can find great potentials in the RF wireless communications [3, 4].

It is well known that OAM-carrying beams have the features of helicoidal wave-front, azimuth phase dependency of $\exp(il\varphi)$ (l is OAM mode number and φ is the azimuthal angle), and an amplitude null in the center of the beam [5]. Due to the divergence of OAM beams, the further they travel, the larger the radius of the 'dark zone' around the amplitude null is. Moreover, the larger the OAM mode number l, the more severe the divergence. This feature brings a challenge when receiving the OAM beams after long distance transmission. In order to receive sufficient energy, conventional whole angular aperture receiving (WAAR) scheme should have a very large aperture – larger than the dark zone, which may not be feasible in practice. For example, in satellite-to-ground free space optical communication, the required whole-beam receiving aperture can be very large indeed [6]. The problem is more pronounced in low frequency (e.g., RF) OAM communications.

Several papers had reported the relationship between the OAM mode spectrum and the angular aperture [7–9]. It is concluded that the OAM spectrum is the discrete Fourier transform of the azimuthal dependence of aperture function [9]. With restricted aperture, new OAM sidebands will be generated and the crosstalk occurs, which makes the partial receiving not so appealing as its compactness. In the last decade, various means to sort and detect OAM state or superposition states have been proposed [10–12], yet most of them needs complicated post-process, especially for demultiplexing multi-OAM channels in optical communication. In [13, 14], the relationships between the aperture sizes, the mode interval and the minimum crosstalk, and the performances for the single and double partial receiver apertures schemes were experimentally demonstrated. It was shown that the crosstalk resulting from the restricted aperture could be improved by using proper partial receiving.

In this paper, a novel partial angular aperture receiving (PAAR) scheme is proposed and demonstrated. Instead of using the whole angular aperture of 2π, only part of the angular aperture is used at the receiver. Figure 1 shows the schematic of PAAR and WAAR schemes. Although this PAAR scheme cannot afford orthogonality to all the OAM modes transmitted, it may provide ideal orthogonality for a regular set of OAM modes, using which independent channels can be established in the optical communication. The theoretical principle is firstly analyzed, then the proof-of-principle experiment results are presented, and finally the advantage and the disadvantages of this scheme are discussed.

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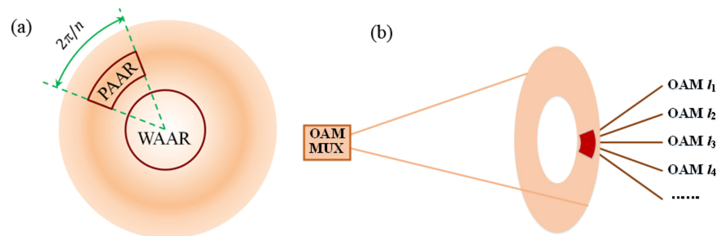

Fig. 1. (a) Schematic of partial angular aperture receiving (PAAR) and whole angular aperture receiving (WAAR); (b) PAAR based OAM multiplexing communication system.

2. Theoretical principle

The field of the OAM-carrying beams in the cylindrical coordinate can be written as,

$$\psi(\rho,\varphi,z) = A(\rho,z)e^{il_1\varphi} \tag{1}$$

where l_1 is the integer OAM mode number of the transmitting wave, and $A(\rho,z)$ is a function related to the transmission distance z and radius ρ. Generally at the receiver end, the demultiplexing device with the phase distribution of $\exp(-il_2\varphi)$ is used to demodulate the helical phase of the transmitted OAM carried beam, where l_2 is also an integer. If we use the WAAR scheme without angular restriction, the received field can be described as

$$U = \int_0^{\rho} A(\rho,z)\rho d\rho \int_0^{2\pi} e^{il_1\varphi}e^{-il_2\varphi}d\varphi = \int_0^{\rho} A(\rho,z)\rho d\rho \int_0^{2\pi} e^{i(l_1-l_2)\varphi}d\varphi \tag{2}$$

Clearly, if $l_1 = l_2$, the received beam has a planar phase front and the on-axis intensity are generated. When the receiver's aperture is larger than the dark zone and contains the first main lobe, the received power has a relative large value, which means the transmitted beam of OAM mode l_1 can be obtained. However if $l_1 \neq l_2$, the integration is zero, meaning the designed demodulation device for OAM mode of l_2 cannot be used to receive the beam carrying OAM mode of l_1, which verifies that different OAM modes are naturally orthogonal to each other.

For the PAAR scheme, as the receiver uses an angular aperture of $2\pi/n$, Eq. (2) can be modified as

$$U = \int_{\rho_1}^{\rho_2} A(\rho,z)\rho d\rho \int_0^{2\pi/n} e^{il_1\varphi}e^{-il_2\varphi}d\varphi = \int_{\rho_1}^{\rho_2} A(\rho,z)\rho d\rho \int_0^{2\pi/n} e^{i(l_1-l_2)\varphi}d\varphi \tag{3}$$

The integration in Eq. (3) will not be zero for all the case of $l_1 \neq l_2$, which means that the PAAR scheme cannot guarantee the orthogonality between all the OAM modes received. Hence it is not applicable to arbitrary multi-OAM-mode transmission and receiving. However, for $l_1 - l_2 = mn$, m is an integer, assuming $\varphi' = n\varphi$, Eq. (3) is

$$U = \frac{1}{n}\int_{\rho_1}^{\rho_2} A(\rho,z)\rho d\rho \int_0^{2\pi} e^{im\varphi'}d\varphi' = \begin{cases} 0 & m \neq 0 \\ \dfrac{2\pi}{n}\displaystyle\int_{\rho_1}^{\rho_2} A(\rho,z)\rho d\rho & m = 0 \end{cases} \tag{4}$$

The case $m = 0$ in Eq. (4) shows that by using the PAAR scheme the power of transmitted OAM mode can be partially obtained once the phase is correctly demodulated. More importantly, the case $m \neq 0$ shows that the PAAR scheme can afford ideal orthogonality to a certain set of OAM modes. For the receiver with the angular aperture of $2\pi/n$, the set includes

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a series of OAM modes with $l_m = l_1 - mn$, which are orthogonal to each other, and can be used for multiplexing due to the inherent low crosstalk. This provides an easy scheme for the demultiplexing of the multi-OAM-mode links and will bring many benefits as the PAAR scheme can significantly reduce the receiver aperture, especially in the situation of long distance transmission.

3. Proof-of-principle experiments

Proof-of-principle experiments are carried out in the optical regime. Figure 2(a) shows the experimental setup for demonstration of the PAAR scheme. The beam emitted from a continuous-wave laser source at 1550nm with fiber pigtail is firstly collimated to a 6mm diameter Gaussian beam by an objective lens. A spiral phase plate (SPP, 10mm × 10mm) is used to optionally transform the beam to an OAM carrying beam with mode number of between −8 to + 8. A reflective spatial light modulator (SLM) programmed with the analyzing hologram patterns is employed to demultiplex and analyze the transmitted OAM beams. A linear polarizer (LP) is inserted in the optical path to realize the required polarization state for SLM. The light reflected from the SLM and mirror transmits through a lens and finally recorded by an infrared camera [7]. The last lens acts as the optical Fourier transformer, in which the integration similar to Eq. (4) is done, which can verify the orthogonality of the OAM modes by monitoring the center intensity of different diffraction beams.

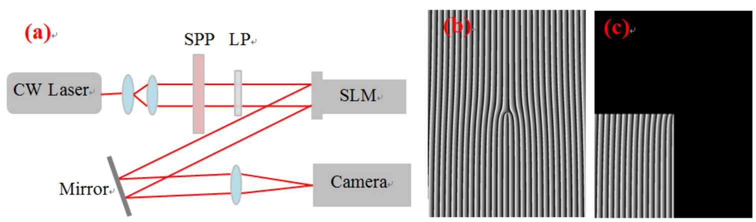

Fig. 2. (a) Experimental setup for the PAAR scheme; (b) the horizontally separated fork grating for $l_2 = -2$ without angular restriction, and (c) with angular restriction of π/2.

The hologram patterns on the SLM are fork gratings programmed as the sum of two phase patterns: the spiral phase pattern of $\exp(-il_2\varphi)$, which is designed to spatially demodulate the phase of the transmitted OAM beams, and a blazed grating, which is used to horizontally or vertically separate the demodulated beams from other diffraction orders. Figure 2(b) shows a fork grating without angular restriction, with which the −1st diffraction is dominant, while Fig. 2(c) is the same pattern but restricted by an angular aperture of width π/2. Since the other three fourths of the pattern are uniformly phased, the corresponding incident power will be reflected and shown as the 0th order. Here, the designed $l_2 = -2$.

To verify the feasibility of the PAAR scheme, the OAM carrying beam of $l_1 = -2$ is transmitted using a SPP, and the fork gratings with l_2 of –6 to + 6 and with angular restriction of π/2 are used on the receiving unit. The diffracted beams are recorded by the infrared camera. Figure 3 shows the results. The spot on the right is the 0th order diffraction, while the spot on the left is the −1st order diffraction (demodulated OAM beam), and the red circle is the center of the −1st diffraction spot. For comparison, the diffraction beam demodulated by the WAAR of $l_2 = -2$ is also shown in the bottom-right picture. Due to the reflection from the 3/4 uniformed phase area, the 0th order diffraction is strong for all the PAAR schemes, whereas it is completely dark for the WAAR scheme. As for the −1st diffraction of $l_2 = -2$, the power from the WAAR is much stronger than that from the PAAR. It is not surprising as the PAAR only receives one fourth of the demodulated OAM power in this case.

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It can be observed from Fig. 3 that the pure OAM spectrum of a light beam transmitted through a restricted angular aperture will suffer from angular diffraction [9], which will generate discrete patterns in the OAM spectrum. Hence, at the receiver unit, if the l_2 value of the fork grating is the same with the OAM mode l_1 included in the diffraction spectrum, the resulting beam becomes a plane wave and will be focused on the center of the −1st diffraction spot, otherwise, the resultant beams are transformed to OAM beams with helical phase of $\exp\left[i(l_1 - l_2)\varphi\right]$. The larger $\left|l_1 - l_2\right|$ is, the further the −1st order diffraction is away from the center. Also, as the hologram pattern is of restricted angular aperture of π/2, the recorded −1st diffraction spot is not from a whole OAM beam, but is from the 1/4 beam projected on the aperture. Importantly, for l_2 = 6, 2 and −6, there is no power in the center of the −1st diffraction spot, which agrees with the conclusion in Eq. (4). In this case the restricted angle of π/2 corresponds to n = 4, for $l_2 - l_1 = 4m$, where m is an integer, the power in the center of the −1st diffraction spot can hardly be detected as the integration over the angular aperture of π/2 is zero.

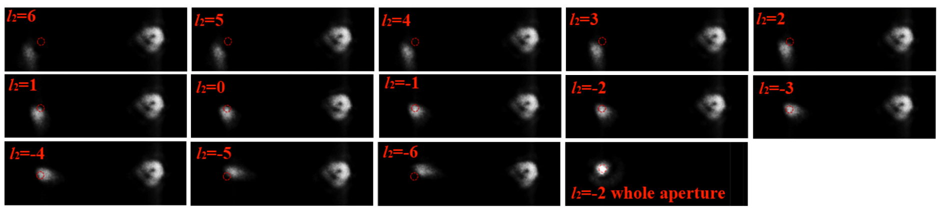

Fig. 3. The recorded −1st and 0th diffraction when the OAM beam of $l_1 = -2$ is demodulated by fork grating of $l_2 = -6$ to 6 with restricted angular aperture of π/2.

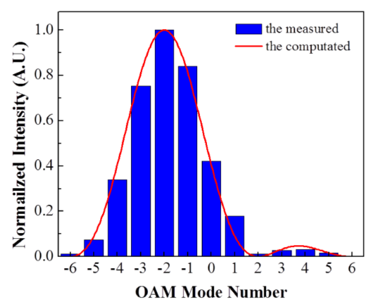

Fig. 4. The distribution of the OAM spectrum when the OAM beam of $l_1 = -2$ is received by an angular aperture of π/2.

Figure 4 shows the OAM spectrum when the OAM beam of $l_1 = -2$ is received with an angular aperture of π/2. It is calculated by integrating the power in the center of the −1st diffraction spot with a square of 11 × 11 pixel. Clearly, the PAAR scheme will introduce extra OAM mode sidebands due to the angular diffraction, which gives a typical sinc^2 envelope. The red line in Fig. 4 is the computed data of sinc^2 function. Hence, it can be concluded that with the PAAR scheme, the power of the transmitted OAM mode is dominant; the power of angular-diffracted OAM side-modes meet a sinc^2 distribution. The adjacent OAM modes to the transmitted beam are relatively large, however, for some regularly spaced OAM modes, depending on the angular aperture used; their power is negligible and results in a large side-mode suppression-ratio (SMSR). This feature forms the main basis for the demultiplexing with a limited angular aperture in the multi-OAM-mode transmission.

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In a further experiment, four blocks of hologram designed for demultiplexing the OAM modes of −6, −2, 2, and 6, each of an angular aperture of π/2, are combined into a single pattern as shown in Fig. 5(a). With the help of the vertical and horizontal blazed gratings, OAM modes of $l = -6$ and −2 can be horizontally separated, while OAM modes of $l = 6$ and 2 can be vertically separated. The corresponding −1st diffraction positions are shown in Fig. 5(b). The pattern in Fig. 5(a) is used to further demonstrate the orthogonality of such a set of OAM modes. The diffraction images are recorded when the transmitted OAM modes are of $l = -2$ and −6, as shown in Fig. 5(c) and (d), respectively. The four red circles in the figures mark the center positions of the −1st order diffraction images for each OAM modes. It can be seen that the transmitted OAM modes of $l = -2$ and −6 can be successfully received at their expected positions. Meanwhile, no power is received in the center of the other three positions. The results further prove that these OAM modes are orthogonal to each other. If four OAM modes of −6, −2, 2, and 6 are multiplexed, it is easy to demultiplex them simultaneously with this kind of compact PAAR scheme. Compared with the conventional N-mode projection measurements, which are always limited by a success rate of $1/N$ [10], PAAR is much more efficient and cost-effective.

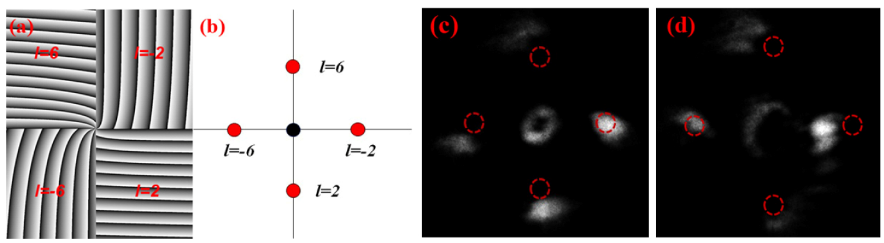

Fig. 5. (a) The pattern combined with four hologram patterns designed for demulplexing of OAM modes of −6, −2, 2, and 6, each with an angular aperture of π/2; (b) the diffraction position for OAM modes of −6, −2, 2, and 6; (c) and (d) the measured diffraction images for the transmitting OAM modes of $l = -2$ and $l = -6$, respectively.

PAAR is realized at the cost of the OAM spectrum efficiency, which is decreased by a factor of n, however, there still exist infinite number of such regular orthogonal eigenstates as the OAM mode number is infinite by itself. Another concern for the PAAR scheme is the power efficiency, because only a portion of the power is detected and received compared to WAAR with infinitely large aperture. Yet, when compared with WAAR under limited aperture size, a PAAR scheme with the same aperture area can be placed at the maximum of the OAM annular mode, as shown in Fig. 1, therefore can actually be more power-efficient than WAAR. For the case that the aperture of the WAAR is not large enough to contain the first main lobe of the OAM beam, PAAR provides a feasible solution. In fact, the power lost in both WAAR and PAAR schemes is dependent on many factors, such as the aperture size, the radius of the maximum field amplitude of an OAM beam, the demultiplexing scheme, and so on. It should be considered comprehensively according to the specific applications.

4. Conclusions

In this paper we proposed a novel partial angular aperture receiving scheme for OAM multiplexing communication systems. Using a restricted angular aperture of $2\pi/n$, an arbitrary OAM mode of l is proved to remain orthogonal with the OAM mode set of $l + mn$, m being an integer. The OAM modes among this OAM mode set can be easily demultiplexed when they are transmitted together. At the receiver end, a more compact and cost saving unit can be achieved based on this scheme. The principle of the PAAR scheme is not only applicable to the free space optical OAM communications, but also to RF OAM communications. We believe it may have greater significance for the latter, as in the RF regime, the divergence of the OAM mode is even more severe and beam focusing devices are not as effective as lens in the optical regime. The proposed PAAR scheme may provide a cost-effective and space-saving method for multi-OAM-mode transmission, especially in long distance links.

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